Polar Geosci., 12, 143–156, 1999

MINERALOGY OF SCAPOLITE FROM SKALLEN IN THE LÜTZOW-HOLM BAY REGION, EAST ANTARCTICA

Isao KUSACHI[1], Yasuhito OSANAI[1], Tsuyoshi TOYOSHIMA[2], Masaaki OWADA[3], Toshiaki TSUNOGAE[4], Tomokazu HOKADA[5] and Warwick A. CROWE[6]

[1]*Department of Earth Sciences, Okayama University, Tsushima-naka 3-chome, Okayama 700-8530*
[2]*Graduate School of Science and Technology, Niigata University, Ikarashi 2-chome, Niigata 950-2181*
[3]*Department of Earth Sciences, Yamaguchi University, Yoshida 1677–1, Yamaguchi 753-8512*
[4]*Department of Earth Sciences, Shimane University, Nishi Kawatsu, Matsue 690-8504*
[5]*Department of Polar Scinece, School of Mathematical and Physical Scineces, The Graduate University for Advanced Studies, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*
[6]*Department of Geology and Geophysics, University of Western Australia, Nedlands, Perth 6970, Australia*

Abstract: Two types of zoned scapolite in calc-silicate gneisses from Skallen, East Antarctica, were found. One type varies from Me_{79} in the core to Me_{35} at the rim. Associated minerals are mainly diopside, pargasite and spinel. The other varies from Me_{33} in the core to Me_{57} at the rim. Associated minerals are mainly diopside, phlogopite and K-feldspar (Or_{95-99}). Scapolite in this specimen contains characteristically K, and the substitution of K in the M site is 8–12%.

The unit cell dimensions of scapolite (Me_{42-45}) from Skallen are a=12.121(1), c=7.585(2) Å, and those (Me_{77-83}) from Sri Lanka are a=12.164(1), c=7.568(1) Å. These scapolites belong to different isomorphous series.

It is likely that the zonation and K-substitution of scapolites from Skallen appear to be formed by a reaction with minerals in direct contact and/or fluids in later stage alteration.

key words: scapolite, meionite, marialite, zonal structure, Skallen, East Antarctica

1. Introduction

The mineral scapolite refers to a family of framework aluminosilicates with tetragonal symmetry. The general formula is $M_4T_{12}O_{24}A$, where the major components are M=Na and Ca, T=Si and Al, and A=Cl, CO_3 and SO_4. The mineral group has only two presently accepted species. The idealized end-member formulas are meionite (Me) $Ca_4Al_6Si_6O_{24}CO_3$ and marialite (Ma) $Na_4Al_3Si_9O_{24}Cl$. The mineral displays a wide range of solid solution. According to TEERTSTRA and SHERRIFF (1996), however, the scapolite group has been subdivided into three isomorphous series; Me_{100}-Me_{57} (Ca-rich), Me_{57}-Me_{20} (intermediate), Me_{20}-Me_0 (Na-rich).

Scapolite is unique among rock-forming minerals in that it contains information

about the activities of volatiles, and is fairly widely distributed in metamorphic rocks, especially those rich in Ca, and stable over a wide range of pressures and temperatures (SHAW, 1960 and others). Stability relations and phase equilibria have been studied by ORVILLE (1975), GOLDSMITH and NEWTON (1977), AITKEN (1983), BAKER and NEWTON (1995) and others.

During our mineralogical survey of the calc-silicate gneisses collected by the geologists of the 39th Japanese Antarctic Research Expedition (JARE) in the Skallen region, Lützow-Holm Bay, East Antarctica, two-types of zoned scapolite were found. One varies from Me-rich in the core to Ma-rich at the rim, and the other from Ma-rich in the core to Me-rich at the rim. MATSUEDA *et al.* (1983), HIROI *et al.* (1987) and SHIRAISHI *et al.* (1994) reported the chemical compositions of scapolites from the Cambrian Lützow-Holm Complex in East Antarctica. But, they have not reported the occurrences of remarkably zoned scapolites. As far as we know, the remarkably zoned scapolite is the first occurrence to be reported in East Antarctica. Moreover, scapolites from the Highland Complex, Sri Lanka, which is considered to have been situated close to East Antarctica before the breaking up of Gondwanaland, were also analyzed for comparison. The present paper deals with its mode of occurrence and mineralogical properties. A more comprehensive study including petrological features will be presented elsewhere.

2. Geological Outline

The Skallen region is situated on the east coast of Lützow-Holm Bay, *c.* 60 km south of Syowa Station, East Antarctica (Fig. 1). Detailed geological investigations of the Skallen region have been carried out by JARE (*e.g.* YOSHIDA *et al.*, 1976). During the 1997–1998 austral summer, the summer party of JARE-39 performed a careful and scrupulous geological survey in the Skallen area (OSANAI *et al.*, personal communication). The area is underlain by various kinds of metamorphic rocks and later intrusions of granitic and pegmatitic rocks. The metamorphic rocks, which belong to the granulite-

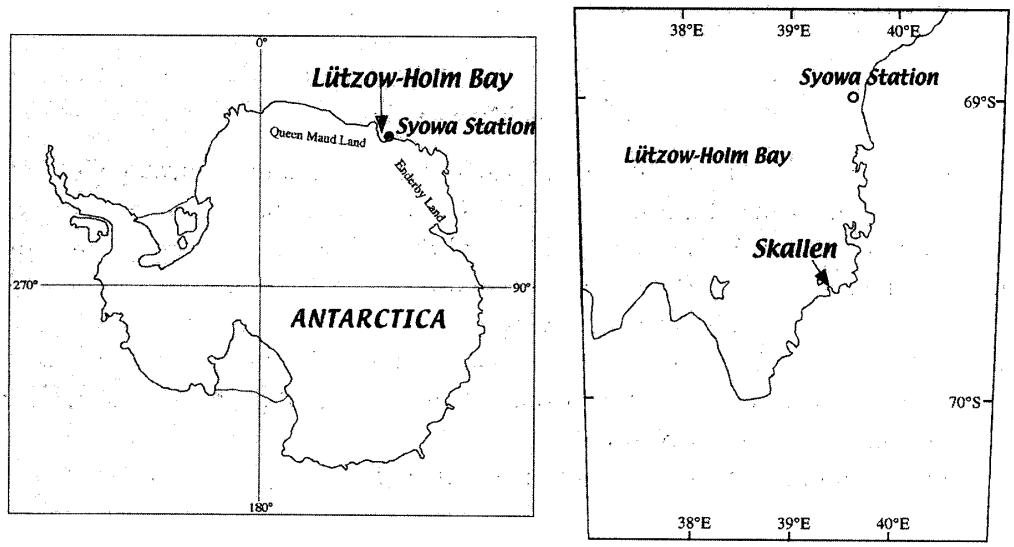

Fig. 1. Location map of Skallen in the Lützow-Holm Bay region, East Antarctica.

facies part of the Lützow-Holm Complex (HIROI *et al.*, 1987), are composed mainly of garnet-bearing quartzo-feldspathic gneiss, garnet-hornblende gneiss, and two pyroxene-hornblende gneisses with subordinate thin intercalations of garnet-sillimanite gneiss, garnet-orthopyroxene gneiss, charnockite, impure marble and skarns. Partly these gneisses form thin alternation zones on the mappable scale.

Lenticular blocks or thin intercalations of impure marbles occur mainly in the northern and southeastern areas. These marbles are normally accompanied by various kinds of skarn-type metamorphic rocks between marbles and surrounding gneisses (Figs. 2 and 3). The skarns discussed here (samples A97122403A and A97122705E) indicate characteristically well-layered structure with compositional banding including the following mineral associations

a) phlogopite-spinel-olivine-calcite,
b) phlogopite-spinel-pargasite-feldspar-calcite,
c) phlogopite-spinel-diopside-feldspar-calcite,
d) scapolite-spinel-phlogopite-pargasite-feldspar-calcite,
e) scapolite-spinel-phlogopite-olivine-feldspar-calcite,
f) scapolite-spinel-phlogopite-diopside-feldspar-calcite,
g) scapolite-diopside-phlogopite-feldspar-calcite.

A97122403A occurs along the E-W trending large shear zone cutting across the region in

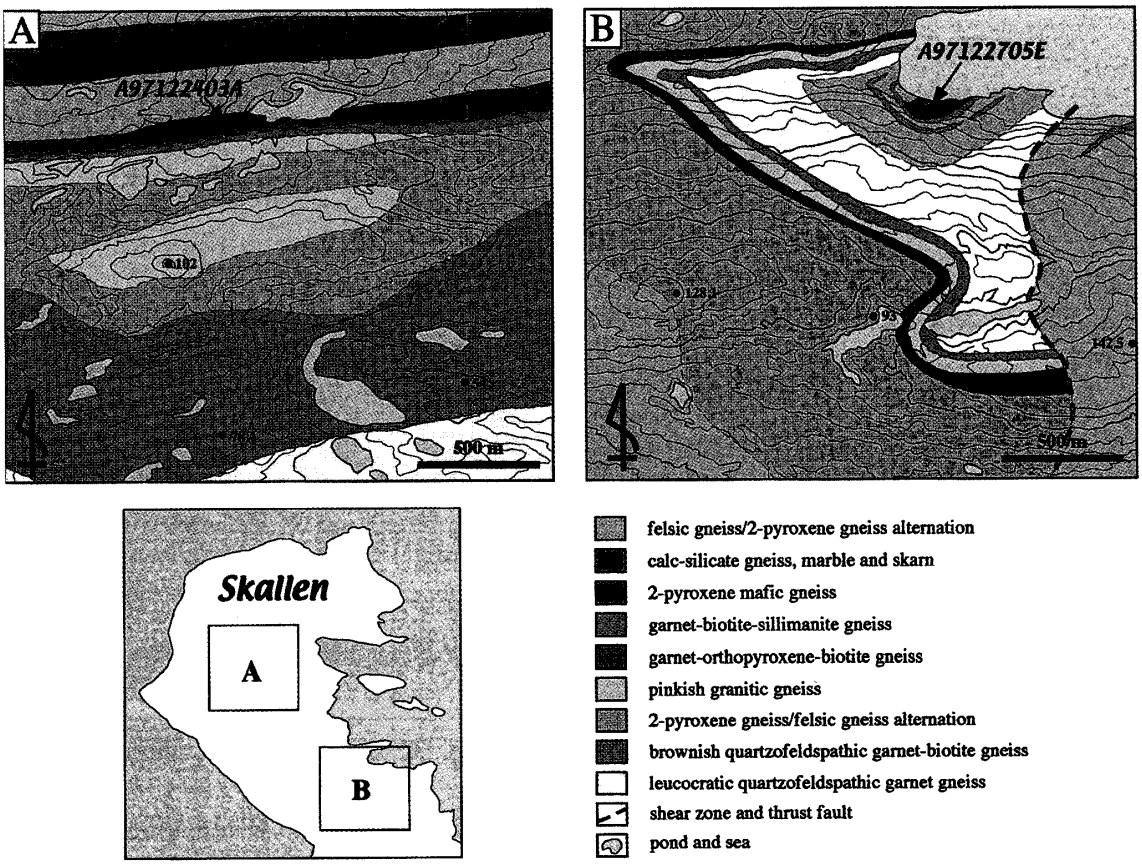

Fig. 2. Simplified geological map of the investigated area in Skallen. A: northern area, B: southeastern area.

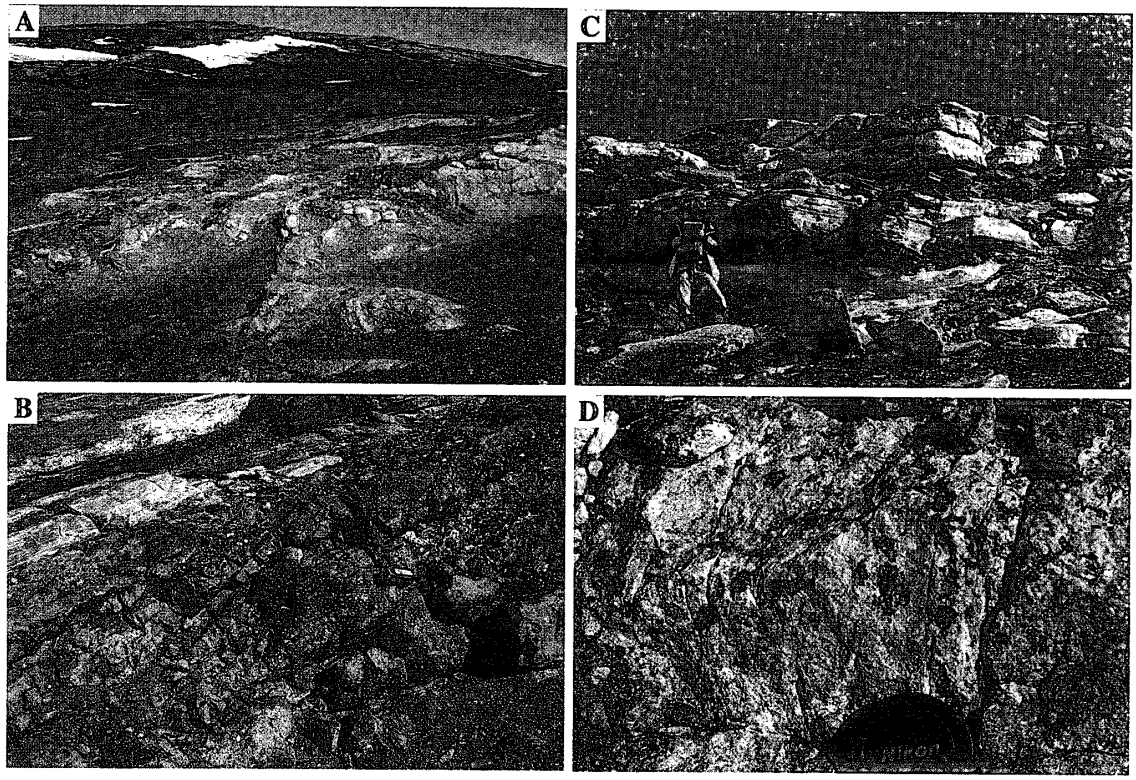

Fig. 3. Modes of field occurrence of scapolite-bearing skarn-type metamorphic rocks in Skallen. A: leucocratic marble and skarn layers along a shear zone (A97122403A), B: close up of skarn-type metamorphic rock (A97122403A), C: thin layered skarn (A97122705E), D: close up of spinel-rich and scapolite-bearing skarn layer (A97122705E).

the northern part, while A97122705E occurs as a lenticular block in the southeastern part (Figs. 2 and 3). Other various mineral assemblages of the skarns are reported from the nearest part of the Skallevikhalsen region (MATSUEDA *et al.*, 1983) where thick marble and skarn layers occur (YOSHIDA *et al.*, 1976; YOSHIDA, 1977).

3. Petrography

Many specimens of calc-silicate gneisses, together with calcite and dolomite marbles, were investigated here. Among these specimens, strongly zoned scapolites occur in two specimens (A97122403A and A97122705E).

A97122403A is composed mainly of scapolite and diopside with subordinate amounts of K-feldspar, phlogopite, apatite, calcite, dolomite and quartz. Scapolite occurs as subhedral to anhedral crystals up to 4 cm in length. The mineral is gray to white in hand specimens, and colorless in thin sections. Under crossed nicols, the mineral shows remarkable variation in birefringence from core to rim. Diopside occurs among scapolite grains. Phlogopite occurs as anhedral inclusions in scapolite and diopside crystals. Apatite occurs sporadically as euhedral to subhedral crystals. Small amounts of calcite and dolomite occur along scapolite grain boundaries, and also are included in scapolite and diopside crystals. K-feldspar also occurs sporadically as anhedral grains in veins intruding into scapolite. Quartz is found locally as grains interlocking with K-feldspar.

A97122705E is composed mainly of scapolite, spinel, phlogopite, plagioclase, pargasite, calcite and dolomite with subordinate amounts of apatite, corundum, rutile and zircon. Scapolite occurs as subhedral to anhedral crystals up to 1.5 cm in length. The mineral is white in hand specimens, and colorless in thin sections. Scapolite is in direct contact with spinel, phlogopite, plagioclase, pargasite, calcite and dolomite. Scapolite shows remarkable variation in birefringence from core to rim. However, in direct contact with plagioclase and symplectitic intergrowth with plagioclase, scapolite shows a slight zonal structure. Spinel occurs as euhedral to subhedral crystals up to 1 cm in diameter, and its color is pale blue in hand specimens. The mineral is also included in phlogopite, plagioclase and scapolite. Phlogopite occurs much more abundantly in this specimen than in A97122403A. Corundum occurs locally as inclusions in spinel. Apatite and zircon occur sporadically as euhedral to subhedral crystals in a small amount. Representative modes of occurrence of zoned scapolite in A97122403A and A97122705E under the microscope from Skallen are shown in Fig. 4.

M88112603A from the Highland Complex, Sri Lanka, is composed mainly of scapolite, diopside, plagioclase, phlogopite, calcite and dolomite with subordinate amounts of titanite and rutile. Scapolite occurs as subhedral to anhedral crystals up to 5 mm in

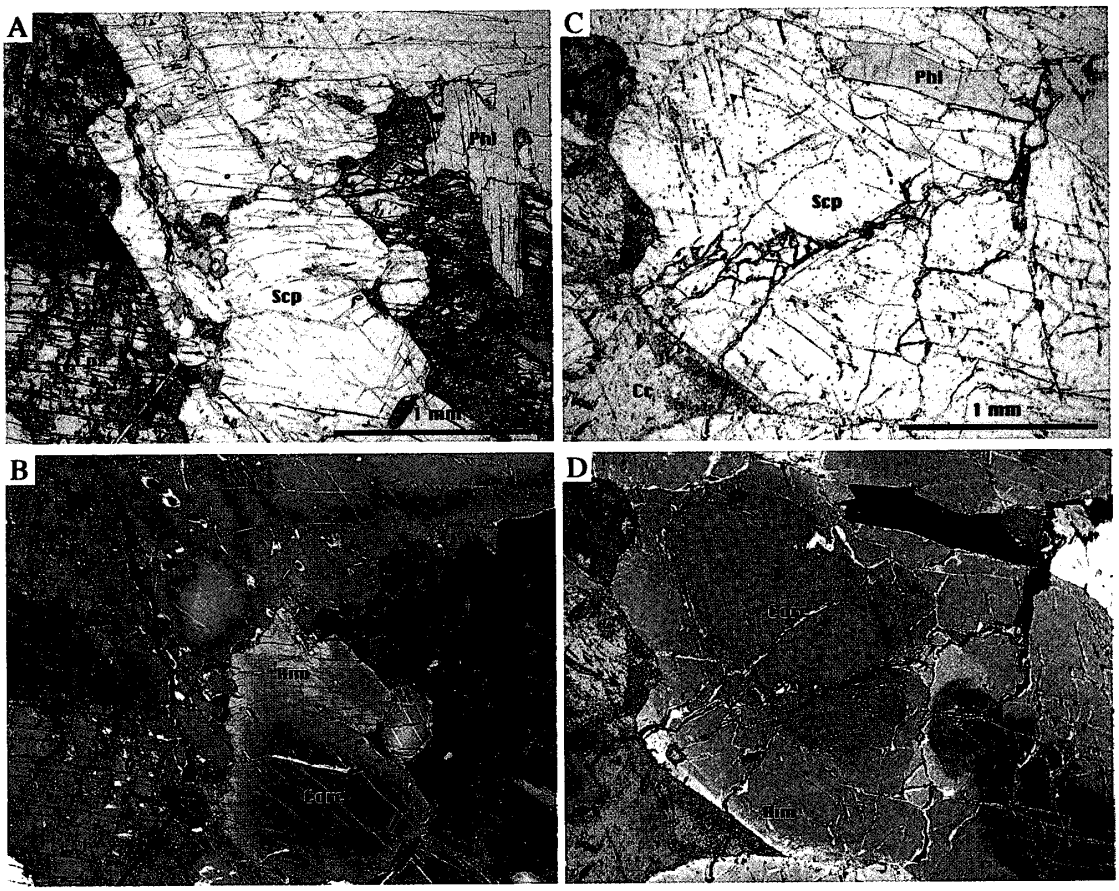

Fig. 4. Photomicrographs showing zoning of scapolite from Skallen. A and B: A97122403A, C and D: A97122705E. The upper two photographs were taken with plane- polarized light and the lower photographs with crossed nicols. Abbreviations: Scp; scapolite, Cpx; diopside, Phl; phlogopite, Cc; calcite.

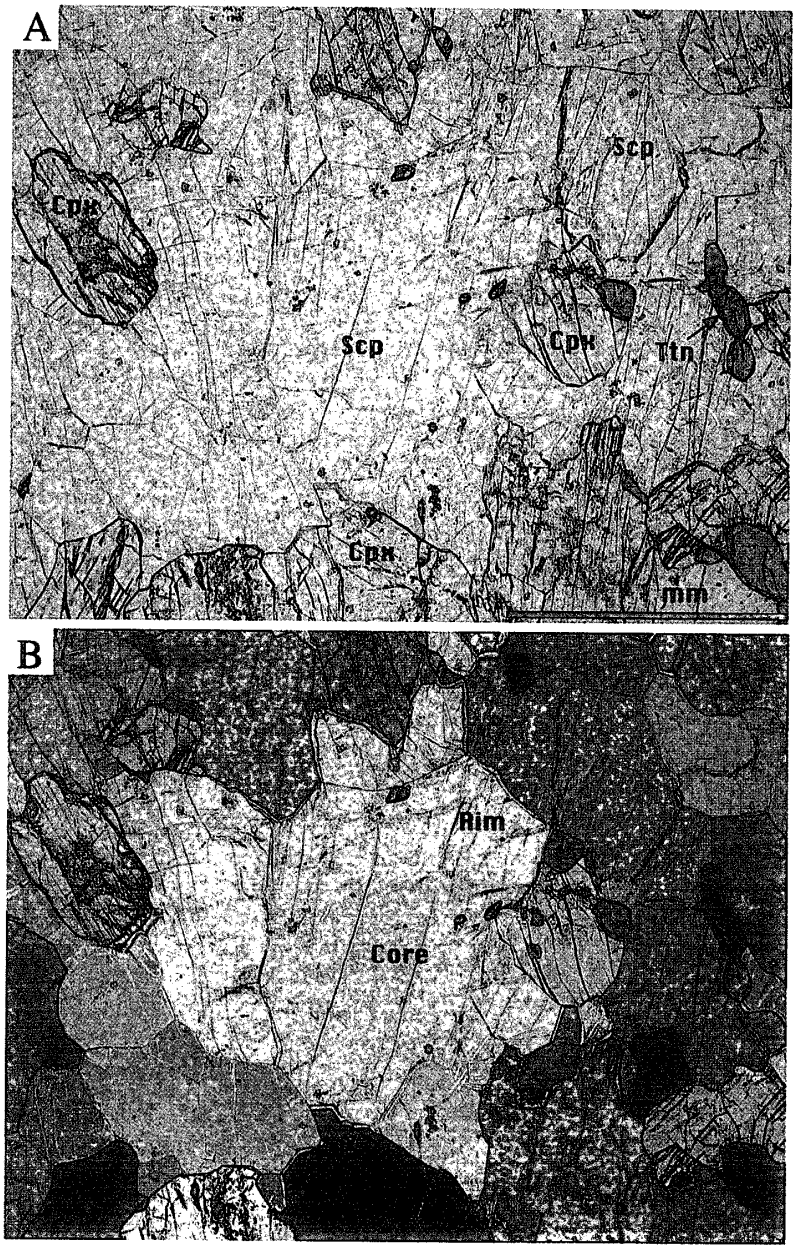

Fig. 5. Photomicrographs of scapolite from Sri Lanka (M88112603A). A: plane- polarized light, B: crossed nicols. Abbreviations: Scp; scapolite, Cpx; diopside, Ttn; titanite.

length. The mineral is white in hand specimens and colorless in thin sections. Scapolite is in direct contact with diopside, plagioclase, phlogopite, calcite and dolomite. A representative mode of occurrence of scapolite in M88112603A under the microscope from Sri Lanka is shown in Fig. 5.

4. Mineral Chemistry

Scapolites were analyzed with energy-dispersive instruments (JEOL JSM-5310S+JED-2400S) with natural mineral standards at Okayama University. Oxide ZAF

correction was applied to analyses. The careful chemical analyses revealed the presence of Cl, and the absence of S, in the scapolites. The elemental maps of the chemical zoning within grains of scapolite in two specimens (A97122403A and A97122705E) from Skallen are shown in Figs. 6 and 7, respectively.

In A97122403A, the map exhibits decreasing Ca and Al, and increasing Na and Cl, from core to rim. In A97122705E, on the other hand, the map exhibits increasing Ca and Al, and decreasing Na and Cl, from core to rim. The chemical analysis of scapolite in A97122403A and A97122705E from Skallen, and M88112603A from Highland Complex, Sri Lanka, was performed from core to rim on a single grain. In A97122403A, the Me content of scapolite varies from 37 mol% in the core to 57 mol% at the rim. Scapolites in this specimen are characteristically rich in K. The substitution of K in the M-site is 8–12%. Associated K-feldspar is Or_{95-99}. In A97122705E, on the other hand, the Me content of the scapolite varies from 79 mol% in the core to 35 mol% at the rim. Scapolite in direct contact with plagioclase and symplectitic intergrowths with plagioclase, however, shows a slight variation in Me content from 79 mol% in the core to 70 mol% at the rim. Associated plagioclase is An_{81-86}. In M88112603A, the Me content of scapolite shows a slight variation from 83 mol% in the core to 70 mol% at the rim.

All analyzed data of scapolites from Skallen and Sri Lanka are plotted in Fig. 8. The

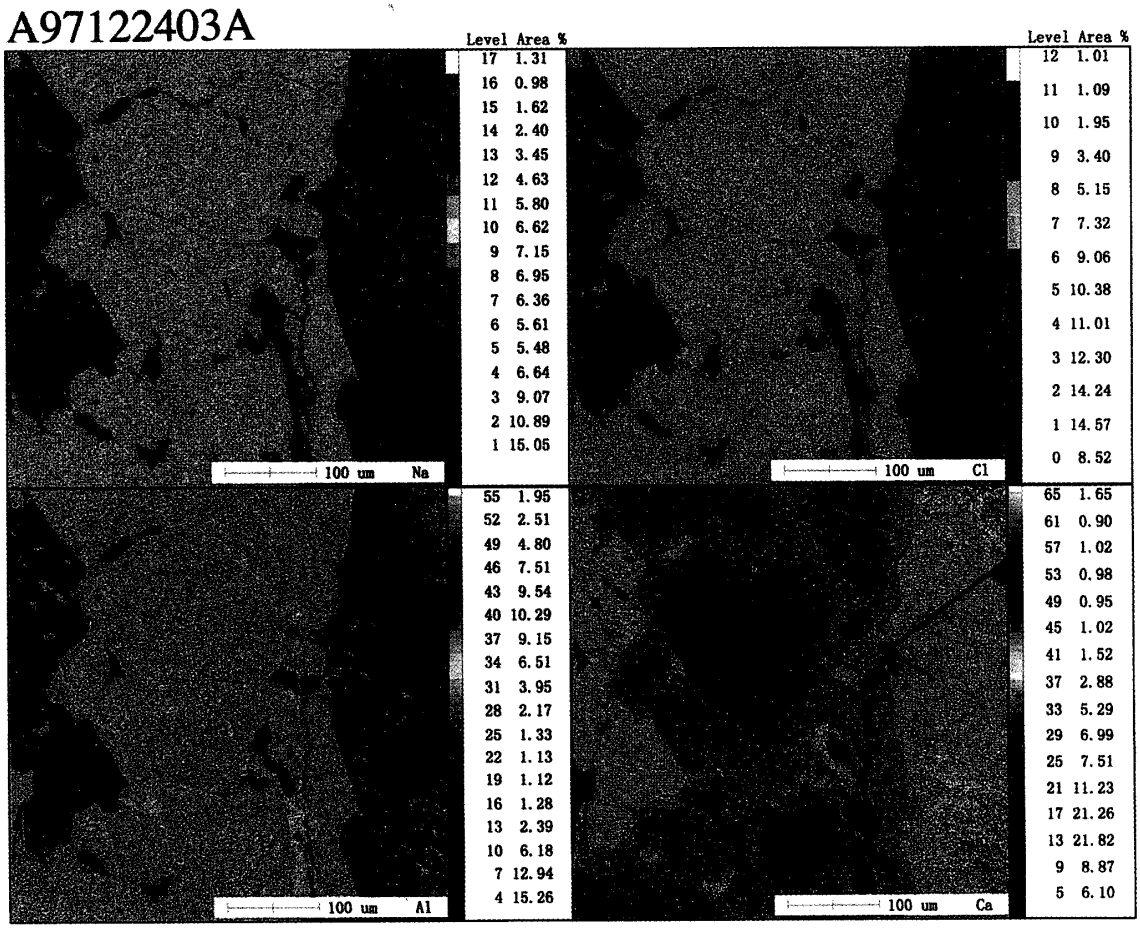

Fig. 6. Na, Al, Cl and Ca zoning of a single scapolite crystal in A97122403A from Skallen.

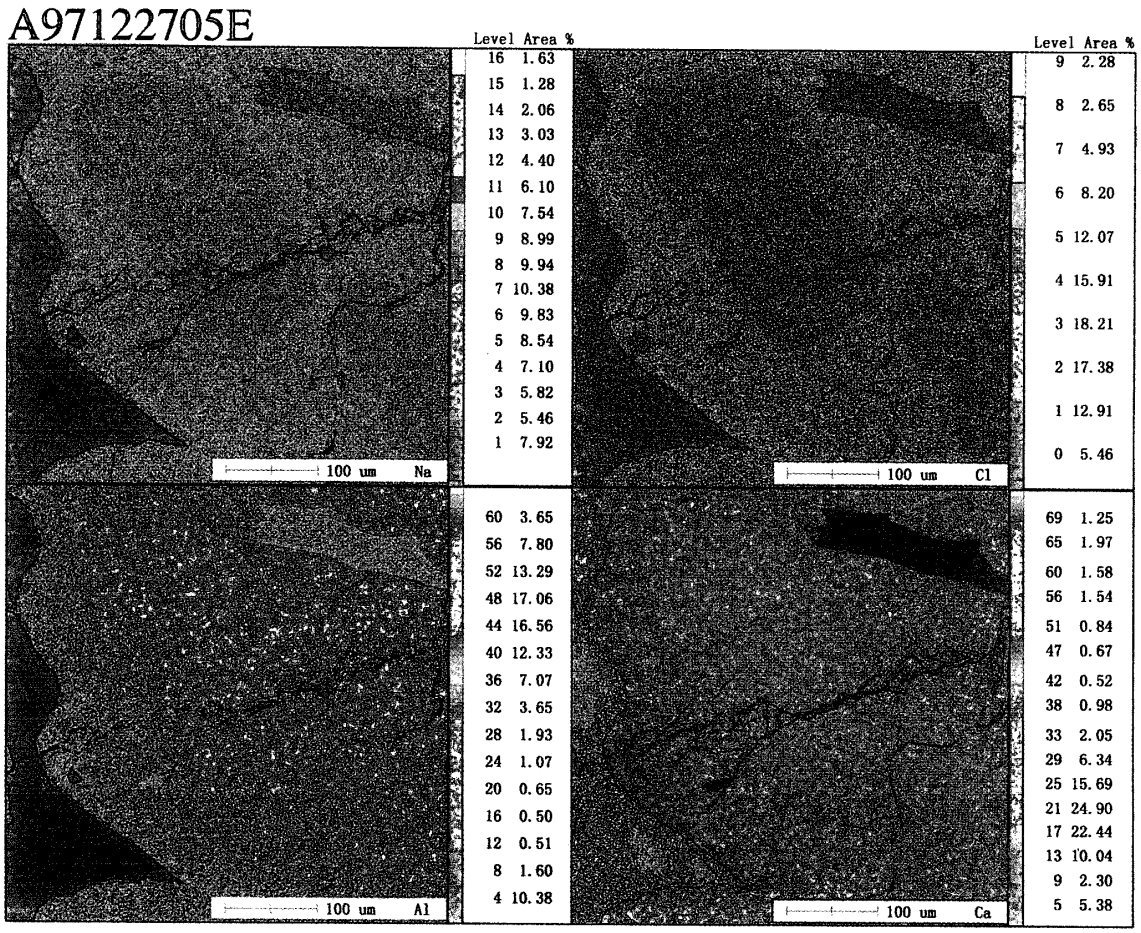

Fig. 7. Na, Al, Cl and Ca zoning of a single scapolite crystal in A97122705E from Skallen.

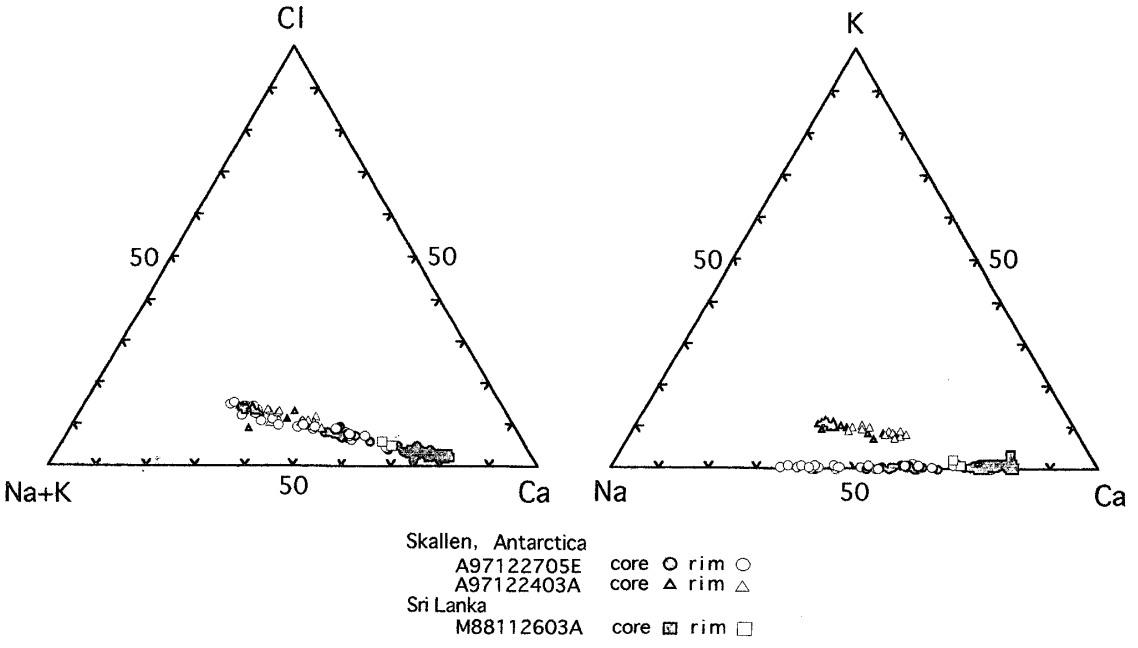

Fig. 8. Cl- (Na+K)-Ca and K-Na-Ca plots for scapolites from Skallen and Sri Lanka.

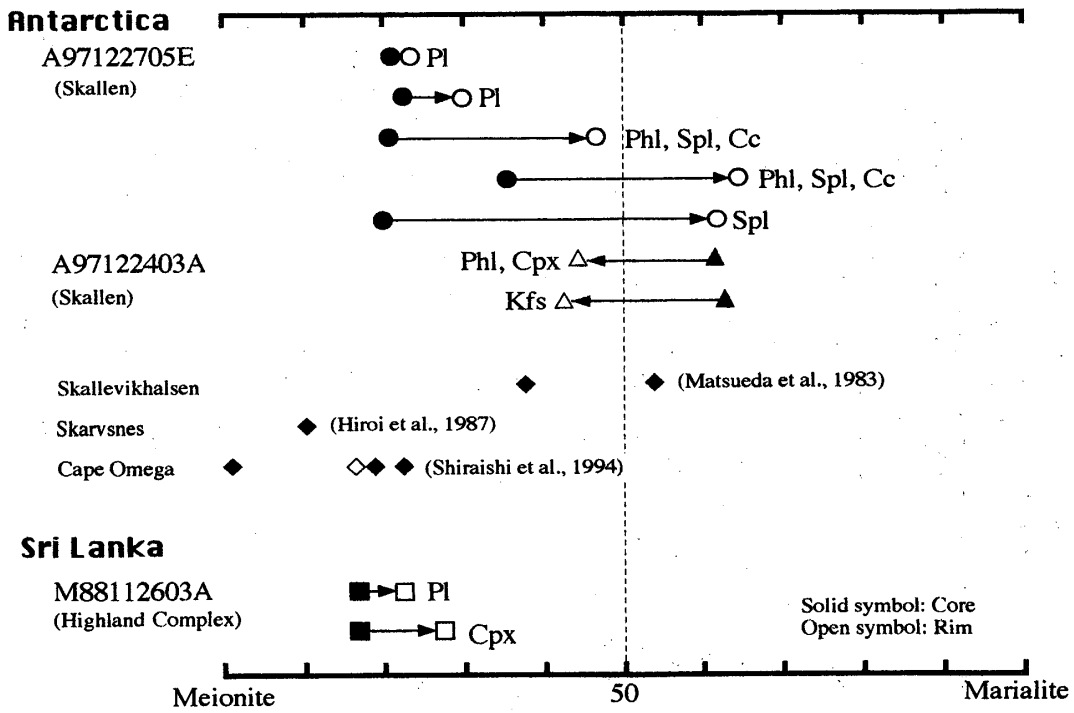

Fig. 9. Representative compositional variation in a single crystal of scapolite from Skallen and Sri Lanka. Abbreviations: Pl; plagioclase, Phl; phlogopite, Spl; Mg-spinel, Cc; calcite, Cpx; diopside, Kfs; K-feldspar.

representative compositional variation in a single grain is shown in Cl-(Na+K)-Ca and K-Na-Ca diagrams (Fig. 9). In the figure, minerals in direct contact with scapolite, and the data reported by MATSUEDA *et al.* (1983), HIROI *et al.* (1987) and SHIRAISHI *et al.* (1994) are also shown. In Tables 1 and 2, representative microprobe analyses of scapolite from Skallen and Sri Lanka are shown.

5. X-ray Study

The X-ray powder data for scapolite from Skallen (A97122403A) and Sri Lanka (M88112603A) were obtained by an X-ray diffractometer using Ni-filtered CuKα radiation, and are given in Table 3. The unit cell dimensions calculated from the powder data from Skallen, which contains Me content of 42–45 mol%, and K of 8–12% in the M site, are a=12.121(1), c=7.585(2) Å. On the other hand, the cell dimensions from Sri Lanka, which contain Me content of 77–83 mol%, are a=12.164(1), c=7.568(1) Å. According to TEERTSTRA and SHERRIFF (1996), end-member meionite has a=12.20 and c=7.556 Å, and marialite has a=12.06 and c=7.551 Å. These cell dimensions are plotted on the trend of cell edge *vs.* Si apfu reported by TEERTSTRA and SHERRIFF as shown in Fig. 10. According to their results, two major changes in trend are located at Si=8.4 apfu and 7.3 apfu, and the scapolite group has been subdivided into three isomorphous series: 7.3>Si>6 (Ca-rich), 8.4>Si>7.3 (intermediate), 9>Si>8.4 (Na-rich). Cell dimensions of scapolite from Skallen are slightly larger than the trend owing to the K content; those

Table 1. Representative microprobe analyses of scapolite in direct contact with phlogopite, spinel, calcite, K-feldspar and diopside from Skallen and Sri Lanka.

	Skallen, Antarctica						Sri Lanka	
	A97122705E				A97122403A		M88112603A	
	core	rim	core	rim	core	rim	core	rim
SiO_2	44.93	47.07	48.78	54.18	52.24	48.77	43.94	46.68
TiO_2	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	28.67	27.02	26.02	23.18	23.41	25.98	28.99	27.24
FeO	0.00	0.51	0.32	0.00	0.10	0.00	0.26	0.10
MnO	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00
MgO	0.25	0.23	0.45	0.21	0.15	0.05	0.26	0.20
CaO	18.27	15.30	14.60	8.58	9.17	14.06	19.37	17.18
Na_2O	3.13	4.89	4.93	8.58	6.76	4.78	2.41	3.73
K_2O	0.24	0.01	0.20	0.09	2.38	1.69	0.12	0.19
Cl	0.46	1.17	1.59	2.76	2.55	1.54	0.47	0.77
-O=Cl	0.10	0.26	0.36	0.62	0.58	0.35	0.11	0.17
Total	95.85	96.15	96.53	97.22	96.18	96.52	95.71	95.92
				Si+Al=12				
Si	6.849	7.158	7.368	7.978	7.853	7.372	6.751	7.110
Al	5.151	4.842	4.632	4.022	4.147	4.628	5.249	4.890
Ti	-	0.024	-	-	-	-	-	-
Fe	-	0.065	0.040	-	0.013	-	0.033	0.010
Mn	-	-	-	0.032	-	-	-	-
Mg	0.057	0.052	0.101	0.046	0.034	0.011	0.060	0.045
Ca	2.984	2.493	2.363	1.354	1.477	2.277	3.188	2.804
Na	0.925	1.442	1.444	2.449	1.970	1.401	0.718	1.102
K	0.047	0.002	0.039	0.017	0.456	0.326	0.024	0.037
Cl	0.119	0.302	0.407	0.689	0.650	0.394	0.122	0.199
Al/Si	0.752	0.676	0.629	0.504	0.528	0.628	0.778	0.688
Me	75	63	61	35	38	57	81	71
Assoc. M.	Phl, Spl, Cc				Kfs		Cpx	

Table 2. Representative microprobe analyses of scapolite in direct contact with plagioclase and symplectitic intergrowth with plagioclase from Skallen and Sri Lanka.

	Skallen, Antarctica				Sri Lanka	
	A97122705E				M88112603A	
	core	rim	core	rim	core	rim
SiO_2	45.44	46.73	45.99	44.78	45.00	44.62
TiO_2	0.00	0.00	0.30	0.00	0.02	0.18
Al_2O_3	28.14	27.15	27.85	28.25	28.46	28.71
FeO	0.00	0.00	0.08	0.00	0.04	0.04
MnO	0.00	0.22	0.00	0.28	0.00	0.10
MgO	0.25	0.21	0.44	0.25	0.28	0.14
CaO	18.47	16.89	18.02	18.63	19.94	18.96
Na_2O	2.97	3.90	2.87	3.11	2.66	2.29
K_2O	0.04	0.17	0.18	0.22	0.20	0.27
Cl	0.47	0.75	0.59	0.70	0.44	0.38
-O=Cl	0.11	0.17	0.13	0.16	0.10	0.09
Total	95.67	95.85	96.19	96.06	96.94	95.60
			Si+Al=12			
Si	6.937	7.123	7.002	6.883	6.875	6.825
Al	5.063	4.877	4.998	5.117	5.125	5.175
Ti	-	-	0.034	-	0.002	0.021
Fe	-	-	0.010	-	0.005	0.005
Mn	-	0.028	-	0.036	-	0.013
Mg	0.057	0.048	0.100	0.057	0.064	0.032
Ca	3.021	2.758	2.940	3.068	3.264	3.107
Na	0.879	1.153	0.847	0.927	0.788	0.679
K	0.008	0.033	0.035	0.043	0.039	0.053
Cl	0.122	0.194	0.152	0.182	0.114	0.099
Al/Si	0.730	0.685	0.714	0.743	0.745	0.758
Me	77	70	77	76	80	81
Assoc. M.	Pl		Pl (Symplectite)		Pl	

Table 3. X-ray powder data for scapolite from Skallen and Sri Lanka.

	Skallen, Antarctica			Sri Lanka		
h k l	d(calc)	d(obs)	I	d(calc)	d(obs)	I
1 1 0	8.571	8.57	3	8.601	8.58	2
1 0 1	6.430	6.43	5			
2 0 0	6.060	6.07	8	6.082	6.07	16
2 1 1	4.410	4.41	5	4.417	4.42	6
2 2 0	4.285	4.29	6	4.301	4.30	2
3 1 0	3.833	3.832	33	3.847	3.845	27
3 0 1	3.566	3.567	16	3.574	3.571	11
1 1 2	3.468	3.469	100	3.464	3.461	100
3 2 1	3.073	3.074	67	3.081	3.081	80
4 0 0	3.030	3.031	28	3.041	3.040	38
3 3 0	2.857	2.856	4	2.867	2.866	4
2 2 2	2.840	2.840	2	2.841	2.841	4
4 1 1	2.741	2.740	13	2.749	1.748	12
3 1 2	2.696	2.695	39	2.698	2.697	49
5 1 0	2.377	2.377	2	2.386	2.385	2
4 3 1	2.309			2.316		
		2.309	11		2.315	15
5 0 1	2.309			2.316		
3 3 2	2.282	2.283	2	2.285	2.285	3
4 2 2	2.205	2.205	2	2.209	2.209	3
5 2 1	2.158	2.158	5	2.164	2.164	12
3 0 3	2.143	2.143	15	2.142	2.142	15
5 3 0	2.079	2.079	2	2.086	2.086	6
3 2 3	2.021			2.020	2.020	13
		2.019	6b			
6 0 0	2.021					
6 1 1	1.927	1.927	10	1.933	1.933	11
4 1 3	1.917					
		1.916	23			
6 2 0	1.916			1.923	1.924	10
0 0 4	1.896	1.896	18	1.892	1.892	13
5 4 1	1.837	1.836	3	1.843	1.843	4
5 3 2	1.823	1.823	4	1.827	1.827	3
5 0 3	1.750			1.751		
		1.752	4b		1.751	3
4 3 3	1.750			1.751		
5 5 0	1.714			1.720		
		1.714	6		1.720	9
7 1 0	1.714			1.720		
6 4 0	1.681	1.681	3	1.687	1.687	2
7 2 1	1.626	1.626	3	1.632	1.632	2
4 0 4	1.607	1.607	5	1.606	1.607	3
6 1 3	1.565	1.565	6	1.567	1.567	8
5 4 3	1.515	1.515	7			
7 3 2	1.468	1.467	6			
6 6 0	1.428	1.428	6			
a (Å)		12.121(1)			12.164(1)	
c (Å)		7.585(2)			7.568(1)	
Me(mol %)		42~45			77~83	

from Sri Lanka, on the other hand, are in harmony with the trend. Si apfu of scapolite from Skallen and Sri Lanka determined cell dimensions are 7.7(1) and 6.8(1), respectively. Therefore, these scapolites from Skallen and Sri Lanka belong to different isomorphous series.

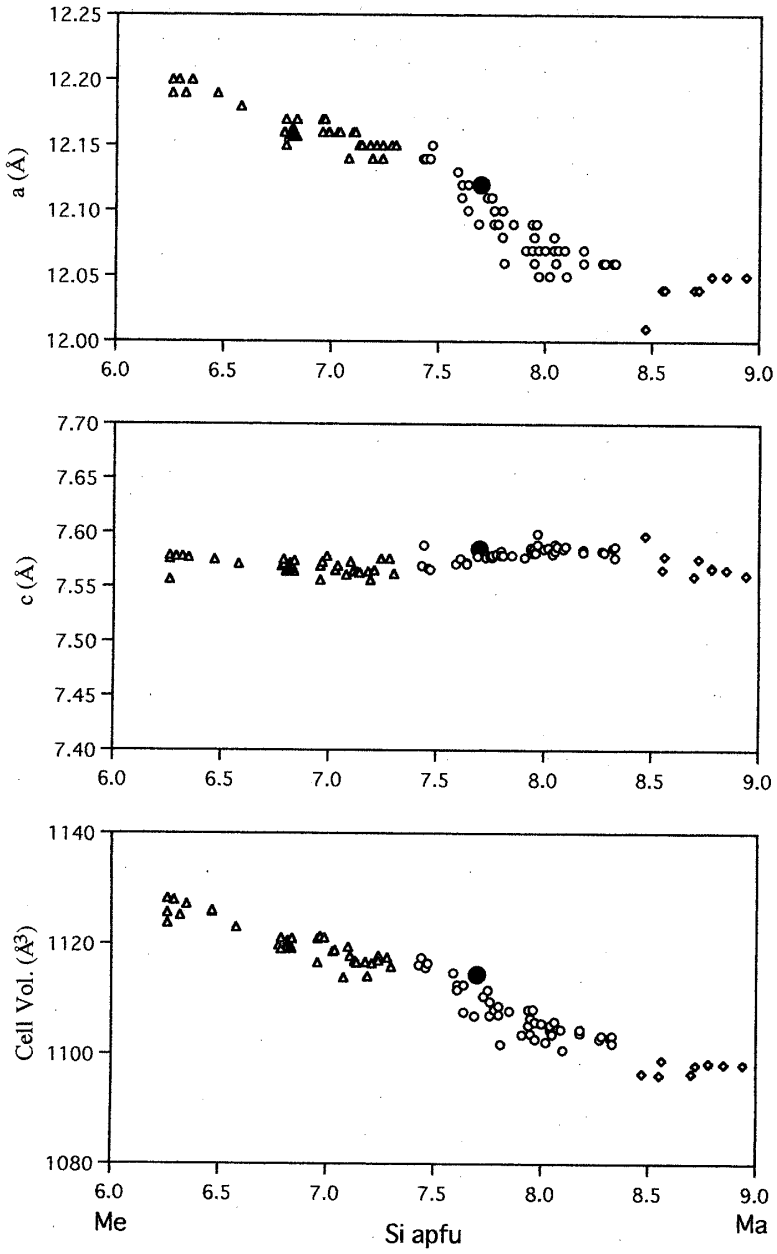

Fig. 10. Plots of cell dimensions vs. Si apfu of scapolite from Skallen and Sri Lanka. Solid circles: Skallen, Antarctica (A97122403A); Solid triangles: Sri Lanka (M88112603A); small open triangles: (Si=6.0–7.3), small open circles: (Si=7.3–8.4) and small open diamonds: (Si=8.4–9.0). Compiled data are after TEERTSTRA *and* SHERRIFF *(1996).*

6. Thermal Behavior

The thermal behavior of scapolites has been studied by GRAZIANI and LUCCHESI (1982), and others. They reported three endothermic peaks with peak temperatures of about 100, 710, and 1030°C in the differential thermal curve. In the present study, the differential thermal curve of scapolite (A97122403A) from Skallen was measured by

heating from room temperature up to 900°C. However, no endothermic peak was found at any temperature.

7. Short Discussion and Concluding Remarks

TEERTSTRA and SHERRIFF (1996) reported that Me content increases with metamorphic grade, and typical samples of high-pressure scapolite are Ca rich. They also reported that under conditions of high temperature and low pressure, scapolites are potentially K-rich if the M-site has increased in volume, and the substitution of K is limited to about 10–20% by the maximum expansion of the M-site.

In the present study, scapolite in A97122705E from Skallen shows high Me content in the core, and the Me content decreases remarkably toward the rim. Therefore, it is likely that the scapolite was formed primarily under the conditions of high-grade metamorphism, and after that, reacted with minerals in direct contact and/or NaCl-bearing fluids along with a decline in pressure and temperature. Scapolite in A97122403A from Skallen varies from Me_{37} in the core to Me_{57} at the rim, and contains 8–12% K at the M-site. The zonation and K-substitution of the scapolite, which changed into Na-rich variety, appear to be formed by reaction with minerals in direct contact and/or $CaCO_3$- and K-bearing fluids along with a re-metamorphism under the condition of high-temperature and low-pressure. On the other hand, scapolites in M88112603A from Sri Lanka show slight variation from Me_{83} in the core to Me_{70} at the rim. Therefore, it is likely that scapolite from Sri Lanka formed under the condition of high-grade (high-T) metamorphism, and was not influenced by fluids very much after the metamorphic peak.

Acknowledgments

We would like to thank sincerely all members of JARE-39. Profs. K. SHIRAISHI and H. ISHIZUKA and Dr. Y. MOTOYOSHI are much appreciated with their encouragement for the severe field work. Thanks are also due to Prof. Y. HIROI and Dr. S. MATSUBARA for critical reading of the manuscript. Two of us (T.H. and W.A.C.) are also grateful to the NIPR and UWA, respectively, for enabling them to carry out the field work.

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(Received March 28, 1999; Revised manuscript accepted May 6, 1999)